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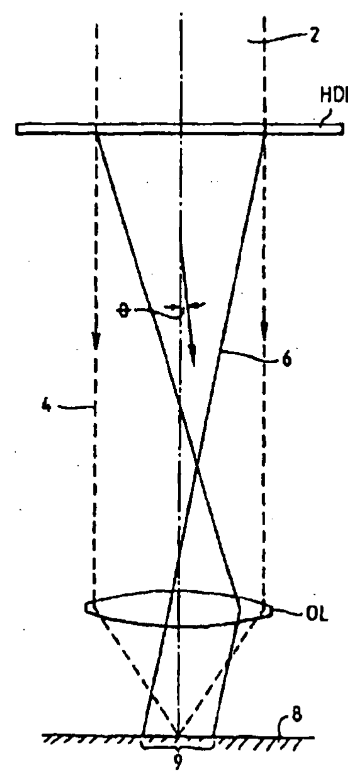
(57) Abstract

Apparatus for phase contrast microscopy or ellipsometry has a source of coherent radiation with a beam divider (HDE) to derive an interrogating beam and a reference beam therefrom which are directed on to a surface under test. An objective receives two scattered or reflected beams which are combined to provide an optical signal indicative of the structure of the surface.



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Optical Measurement

This invention relates to optical measurement, and particularly, but not exclusively, to ellipsometry and profile or topography measurement.

Various proposals have been made for optical systems for topography measurement, such as for measuring the thickness of metal tracks overlaid on a silicon substrate.

Optical methods are very attractive because of their non-contact and nondestructive nature. in addition they have much higher bandwidth than contact methods. Interferometric methods in particular have the potential for measurement of minute height variations in the sub nanometre range (in a 1MHz bandwidth). One overriding problem in the use of such systems for measurement of small topographical changes is that the material variation in the material of the sample can introduce optical phase shifts which swamp the variations due to topography. The other difficulty in obtaining precise measurements is the problem that even small external vibrations (microphonics) can produce phase errors that are larger than the phase changes produced by the topographical variations. In order to overcome this it is necessary to make measurements in an environment which is extremely well isolated from external influences or design the instruments to use common path techniques, by which we mean that both a reference and probe beam transverse almost identical paths so that any microphonics cancel, whereas clearly the information about the sample does not.

According to the present invention, there is provided optical measuring apparatus comprising a source of optical radiation beam producing means for deriving from said source of optical radiation a primary beam and a secondary beam wherein said primary beam is directed on to an object in order to interrogate the local structure of the object and said secondary beam is directed on to said object to serve as an optical reference, optical processing means for deriving from said primary and said secondary beams after reflection from said object a tertiary and a quaternary beam and combining means to combine said tertiary and said quatenary beams to obtain an optical signal indicative of the structure of said object in the vicinity of the surface thereof.

There is also provided ellipsometer apparatus comprising lens means operable to focus light reflected from a sample to a back focal planc. selection means operable to select light of at least two different polaritisations from light arriving at the back focal plane, and measuring means for measuring parameters of the selected light to provide information

from which properties of the sample may be calculated.

Preferably the selection means is operable to select s-polarised and p-polarised components of light reaching the back plane.

Preferably the measuring means further comprise means operable to cause the selected light to interfere. The measuring means may be operable to measure the amplitude and phase of fringes caused by the interference.

The selection means may comprise a mask located at the back focal plane and being open at positions corresponding to the selected polarities, whereby light of other polarities is blocked by the mask. The mask may comprise openings positioned to select s-polarised and p-polarised light

Preferably the selection means comprises a mask, an opening in the mask through which selected light may pass, and separation means operable to separate p-polarised and s-polarised components of light passing through the mask opening. The separation means may spatially separate the components. The separation means may comprise a Wollaston prism.

The selection means may comprise phase separator means operable to apply a differential phase shift to the selected light. The phase separation means may comprise a Pockel cell. The Pockel cell may be selectively operated to vary the differential phase shift to allow respective sets of measurements to be taken by the measuring means.

Lens means may be provided to bring the separated components together to produce interference. The lens means may comprise polariser means aligned with its pass axis bisecting the angle between the p-direction and s-direction.

The invention also provides profile measuring apparatus comprising lens means operable to focus light reflected from a sample to a conjugate plane, selection means operable to select light at two different positions in the conjugate plane, and measurement means for measuring parameters of the selected light from which profile information relating to the sample may be obtained.

The selection means may comprise a mask having openings at two positions. The two positions are preferably symmetrically located either side of the optical axis of the system. The measuring means may comprise means operable to cause the selected light to interfere and may be operable to measure the amplitude and phase of the fringes caused by

the interference. The measuring means may further comprise transforming lens means operable to project a Fourier transform of the light passing through the lens to a plane at which optical interference fringes are formed. Preferably the apparatus further comprises means for measuring the position and contrast of the fringes.

In a third aspect, the invention provides profile measuring apparatus as set out in the preceding two paragraphs, and further comprising ellipsometer apparatus according to any of the preceding definitions. The apparatus preferably further comprises means operable to obtain information relating to sample properties from the ellipsometer apparatus, and to use this information to remove material-dependent information from the measurements obtained from the profile measuring apparatus, to yield substantially pure profile information.

Embodiments of the present invention will now be described in more detail, by way of example only, and with reference to the accompanying drawings, in which:

Fig. 1 is a schematic diagram of apparatus in accordance with an embodiment of the invention;

Fig. 2 shows a phase stepping phase contrast microscope in accordance with another aspect of the invention;

Figs. 3a and 3b illustrate details of the apparatus of Figure 2;

Figs. 4 and 5 are schematic diagrams of ellipsometer arrangements according to different embodiments of the invention;

Fig. 6 is a schematic diagram of a mask for use in the ellipsometer of Fig. 5;

Fig. 7 shows a confocal microscope system;

Fig. 8 illustrates a modification to the system of Fig. 7;

Fig. 9 shows a common path optical interferometer in accordance with a further embodiment of the invention;

Fig. 10 shows a full field ellipsometer constructed in accordance with a further aspect of the invention, and

Figs. 11 is a schematic diagram of profile measuring apparatus incorporating an ellipsometer according to a particular aspect of the invention;

Fig. 12 is a schematic diagram of a mask for use in the apparatus of Fig. 11;

Fig. 13a shows light distribution at a plane within the apparatus of Fig. 12, and

Fig. 13b is a schematic diagram of a mask for use at that plane.

The apparatus to be described is capable of obtaining topography information substantially free of material-related information, the results being called herein "true topography" information. This apparatus incorporates ellipsometer components which themselves form an aspect of the present invention.

The process for extraction of true topography can be broken down into three key stages:

(1) a common path interferometer to obtain sample-related phase information;

(2) a means to obtain information about the material properties of the sample whilst still retaining the full lateral resolution available from the lens numerical aperture;

(3) a general inversion algorithm capable of converting the response of the common path interferometer into a response, free of microphonics, which would be obtained with a surface profiling instrument with the same spatial frequency cut off, such as an optical device or non-optical device (e.g. a stylus probe).

Stages (1) and (3) enable one to achieve common path operation and with the response obtained from an ideal interferometer in the absence of microphonics. Stage (2) provides the correction for material dependent phase shift on the sample.

Figure 1 of the drawings shows one embodiment of the invention. At the heart of the system is a specially designed holographic diffractive component HDE, whose function is to produce, with a collimated incident beam 2 from a radiation source (not shown), three output orders: a zero order collimated object beam 4, a +1 order convergent beam, and a -1 order divergent beam (not shown). The ±1 output beams are designed to propagate at a slight angle θ relative to the optical axis. The effect of the divergent beam is small and can be ignored. The zero order beam is focused on to a sample 8 via a microscope objective OL, and is used to interrogate the local structure of the object. The +1 order beam will be collimated by the objective lens, and will illuminate over a large object area. It serves as a phase reference whose value will remain unchanged as the object is scanned. Upon reflection from the sample surface, the two beams will pass through the hologram a second time, each will generate, among others, a collimated component with a slight difference in their propagation directions. The phase of the resulting interference fringes (nominally parallel) will correspond to the average phase difference of the two light beams and can be

extracted by taking the Fourier transform of the captured intensity pattern. Alternatively, a four element photodiode array can be used to capture one single optical fringe. A standard analogue quadrature signal processing scheme is then used to provide the phase value in real time. Phase fluctuations common to both beams will not affect the positions of the optical fringes and will not appear at the system output.

Figure 2 shows a phase stepping phase contrast microscope in accordance with another aspect of the invention. This system combines optical techniques employed in the phase contrast microscope and the phase stepping interferometer to provide stable and sensitive profile measurements. An object 220 is imaged on to an image plane 222 using a telecentric arrangement, in which a plane 224 is the common focal plane of the two lenses 223, 225. This plane is also the Fourier plane of the object. With the phase contrast technique, a phase plate (shown in plan 226a in Fig. 3b and section 226b in Fig. 3c is inserted in the Fourier plane. This allows the background and the scattered light (due to object features) to interfere in phase, and results in high contrast images. To perform quantitative surface measurement, the system is modified thus: a number of optical images are captured using a CCD array placed at the detector plane 222, each time with a different optical phase plate inserted in the Fourier plane. The minimum number of images required is three, and the three phase plates are such that the first one is uniform and gives zero degree of phase shift, the second one provides a $\pi/2$ phase shift between the background and the scattered light, and the third one provides a π phase shift. The operation of the system is thus similar to that of a phase stepping interferometer, where a number of interferograms are generated, each with the interference condition altered by a known amount. A set of simple conversion equations can then be used to obtain the surface profile and the reflectivity of the object from the captured interferograms. With the phase stepping phase contrast technique, a different set of conversion equations applies. The system can be used to map the surface height variation of an object. Compared with phase stepping systems, the proposed technique does not require a separate reference arm, and is therefore much more compact. Moreover, the two interference beams (background and scattered) travel through the same set of optics; any common mode noises (microphonics and thermal gradients) will affect the two similarly, and their effects will be cancelled. Stable and precise optical measurements can therefore be obtained without the need of expensive

optical isolation station.

Two alternative forms of ellipsometer are shown schematically in Figs. 4 and 5.

The arrangement 70 in Fig. 4 has an optical mask 72 at the back plane in place of the mask 52 of Fig. 1. The optical arrangement upstream of the mask 72 is the same as that shown in Fig. 1.

The optical mask, in its simplest form, consists of one pinhole only. Taking the p- and s- lines as the vertical and horizontal axes, the single pinhole should be located along the 45° line 90. The light beam passing through this hole therefore consists of equal amount of p- and s- polarised components modified by the effect of the respective complex reflection coefficients of the material under inspection. In order to measure the complex reflection coefficients associated with the two, a Wollaston prism 74 is used to separate the two components angularly. The lenses L_1 and L_2 are arranged to convert the two diverging beams into two parallel beams which intersect each other at a small angle. A polariser 76 is placed in between the lenses with its pass axis bisecting the p- and s- directions, thus allowing the two beams to interfere. The two main advantages of this arrangement are:

1. since both the p- and the s- components are originated from the same location, non-uniformity in the input beam distribution does not give rise to any measurement error; and
2. since the interference between the two beams produce a parallel set of fringes, a cylindrical lens can be used to compress the fringes lengthwise, allowing a 1-D detector array to be used. This together with the use of a digital signal processor (DSP) board would lead to near real-time sample measurement.

The optical mask may consist of more pinholes to provide an optical phase reference and improved measurement accuracy.

It can be seen that this arrangement selects the two different polarities of light by using the Wollaston prism to spatially separate the s-polarised and polarised components of light reaching the back plane, and then using the lens system to cause the selected light to interfere, causing interference fringes which are measured at the detector plane. The effect of a single pinhole on the optical axis, following by a Wollaston prism is to create "virtual" pinholes corresponding to the arrangement of Fig. 1, i.e. the light leaving the lens L_1 is equivalent to the light leaving the mask 52 of Fig. 1.

Fig. 5 shows a further arrangement 80 which uses a mask 82 in place of the masks 52, 72 of Figs. 11 and 4 but is identical upstream of the mask 82. The mask 82 has a single pinhole on the optical axis 84.

A long focal length lens L_3 is used to collimate the light beam after the pinhole, and an electro-optical device such as a Pockel's cell 86 is placed after the lens. A second lens L_4; is used to focus the light beam onto a detector 88. The two lenses combined effectively image the pinhole onto the detector plane. The Pockel's cell is oriented so that its two axes are respectively parallel to the p- and s- directions of the light beam, so that when appropriate voltage is applied to the device, differential phase shift can be imposed on to the two polarisation components. The pass axis of the polariser is aligned 45° with respect to both the p- and the s- directions, thus allowing the two components to interfere.

To operate the system, four different voltages are applied to the Pockel's cell consecutively, to effect differential phase shifts of 0°, 90°, 180°, and 270° respectively. After each applied voltage value, the output of the detector is measured. The four outputs are thus given by

$$I_1 = E_1^2\,[\rho_p^2 + \rho_s^2 \;+ 2\,\rho_p\,\rho_s \cos(\Delta)]$$
$$I_2 = E_1^2\,[\rho_p^2 + \rho_s^2 \;+ 2\,\rho_p\,\rho_s \cos(\Delta + 90°)]$$
$$I_3 = E_1^2\,[\rho_p^2 + \rho_s^2 \;+ 2\,\rho_p\,\rho_s \cos(\Delta + 180°)]$$
$$I_4 = E_1^2\,[\rho_p^2 + \rho_s^2 \;+ 2\,\rho_p\,\rho_s \cos(\Delta + 270°)]$$

where E_1 is the amplitude of the light beam, ρ_p and ρ_s are the amplitude reflection coefficients of the p- and s- components respectively. The ellipsometric parameter Δ and $\tan\Psi = \rho_p/\rho_s$ are thus obtained by solving the four simultaneous equations, which can be performed using a personal computer (when solving the simultaneous equations, there is an inherent ambiguity between the values). The system operation procedure is thus similar to that of a phase stepping interferometer, and as such, phase step numbers other than four and different phase shift values may be used. The advantages of this particular configuration are

1. similar to the previous arrangement, non-uniformity in the input beam distribution will not cause any measurement error; and
2. more than one single pinhole along the diagonal lines may be used.

Indeed, for many applications, the preferred optical mask configuration may consist

of two diagonal slits 90 (Figure 6), with the detector 88 replaced by a CCD array. In addition to allowing for more accurate material property measurements, the continuous range of angular frequency components will provide information for more complicated sample structure such as multi-layer thin film. In some measurement situations, the mask may be removed without adversely affecting performance.

It can be seen that the arrangement of Fig. 5 separates light by applying a differential phase shift in the Pockel cell, which is selectively operated to vary the differential phase shift to allow sets of measurements to be taken at the detector plane, with different differential phase shifts. Alternatively, the position of the Pockel cell may be moved to a position intercepting the light beam emerging from the radiation source.

The arrangements 70,80 do not require a uniform distribution across the beam illuminating the sample 12. Furthermore, the arrangement 70 is potentially sufficiently powerful as to allow measurements to be made in real time and can therefore be expected to be particularly useful for monitoring changes in material property, or for making images of a substrate. The arrangement 80 produces measurements of material properties and therefore is particularly useful for studying multi-layer structures.

The final stage in the process involves converting the measured response into an equivalent response that would be obtained with an absolute system. This is achieved in the processor 34. (Fig. 11)

It is important to realise that because the ellipsometry arrangements described above can be used alone to reveal useful information about material properties of the sample 12, this part of the apparatus may be used alone-, without the profiler 28.

Referring now to Figure 7, this shows schematically a conventional confocal microscope. The light from a source 170 passes by way of a partially-reflecting prism 172 and is focussed by an objective 174 on to a sample 176 and imaged back through a pinhole 178 by means of a further lens 180 having a back focal plane 182. The spatial filtering of the pinhole acts to give the confocal microscope its well known characteristics of good axial resolution and improved spatial resolution. The detection process in the confocal microscope can be thought as a two stage process in which the light reflected from the objective is recollimated and refocussed through the pinhole. The distribution at the back focal plane (or any plane conjugate to it) contains the information obtained from an

ellipsometer since the radial position is related to the incident angle on the sample and the azimuthal angle determines the polarisation state of the illumination.

The detection apparatus 178, 180 is shown in the box B of Figure 7. In a further embodiment of the present invention, the addition of a shearing element 184 enhances the functionality of the confocal microscope of Figure 7. The shearing element may typically be an acousto-optic cell which both splits the incoming beam and also introduces a relative frequency shift between the beams. These then pass through the confocal lens 180 which focuses two beams to adjacent spots on the detection plane 186. Note that the shear between the two beams has been exaggerated for diagrammatic clarity and that it is important that the two focal spots in the detection plane overlap. The overlapping focal spots are then spatially filtered with a pinhole of appropriate size, prior to detection in a suitable detection device such as a photodetector. Interference will take place between the two focal spots resulting in the generation of a signal at the difference frequency between the spots. The shear means that effectively different parts of the focal spot interfere with each other so that a highly stable differential phase response results. The degree of shear can be controlled to ensure that desired amount of differentiation by controlling the electronic drive to the shearing device. Moreover, perhaps the greatest merit of the system is that interferometric response can be achieved without a separate reference beam, this results in a very simple and stable system.

Consider placing a detector at point 'a' in the back focal plane of the collimator 180 (Figure 8). This will give an interference signal at the difference frequency between the two beams, this interference will take place at the centre of one of the beams and towards the outer radius of the other. In effect therefore the interference will be between light reflected normally from the sample and light reflected at an oblique angle. The phase difference measured from this interference signal will therefore relate to the different reflection coefficients at different incident angles. This will give an indication of the properties of the sample. Clearly, different detector positions will give information about different incident angles and polarisation states.

The simple addition of one component thus provides a very convenient dual functionality. One gives very stable differential phase image with sensitivity to structural variation on the sample and the later provides a 'differential ellipsometric' mode which will

be very sensitive to variations in the properties of the material which will give a very rapid indication of sample variations such as variations in oxide thickness. It will therefore find particular application in the semiconductor industry.

Referring now to Figure 9, this illustrates a further embodiment of the invention comprising a scanning common path optical interferometer which has good immunity to microphonics and also has good low spatial frequency response. Included in the apparatus is a special lens 190 which is a spherical lens with its central portion replaced by a parallel glass disc. This can be achieved by polishing, to optical flat finish, the central region 191 of a plano convex lens. Ignoring the tilt of the lens for the time being, a parallel beam of fight entering the lens is divided into two sections: the inner portion passes through unaltered and is focussed on to the sample via the microscope objective lens 192. This beam will therefore interrogate the local structure of the object 194; the outer portion of the incident beam passes through the annular lens and is focussed to point P. By arranging P to coincide with the back focal point of the objective lens 192, a collimated annular beam will be incident on the object surface. Since the area of the annulus is large compared to the lateral resolution of the system, it will provide an average reference phase value, which will remain 'unchanged' as the object is scanned. Upon reflection from the object surface, the beams will propagate back through the system a second time. As described, the two beams do not overlap. The diagram shows a compact design which will cause the two beams to interfere, by deliberately tilting the special lens 190 relative to the system axis. This will cause the two beams, after the second passage through the special lens to propagate at an angle to each other. In the region where the two overlap, interference fringes are formed. Any surface height variation will cause the optical phase value of the focussed beam to change, which in turn will shift the positions of the fringes. The latter can be measured by firstly capturing the optical fringes using a CCD camera (not shown), and then applying Fourier transformation to the captured data to provide a measure of the object profile. Alternatively, a photodetector arrays (four elements are sufficient) can be used to capture one single optical fringe. Standard analogue quadrature signal processing scheme can then be used to provide the fringe position in real time. Since the two light beams traverse similar optical path, microphonics will affect the two similarly and their effects will be cancelled in the interference process resulting in a very stable system. Another

advantage that, compared to other common path configurations, the proposed system has a much better low spatial frequency response. The measured profiles can therefore be converted, with high degree of accuracy, to those which confirm with international measurement standards.

Figure 10 shows a full field ellipsometer constructed in accordance with a further aspect of the invention. It may be considered as a standard full field optical microscope in which the angle and polarisation of the illumination is precisely controlled. The initial polarisation state is controlled by a device such as, for instance, the half wave plate 200. The angle of incidence of the input beam 202 is controlled by the illumination optics 204, 206, 208, which focuses the incident light to a point 'a' in the back focal plane 210 of the objective lens 212. The input optics includes a spatial filter 206 and a beam splitter 207. The radial position of this point determines the angle of incidence of the illuminating beam on a sample 214. If the distance of the point 'a' from the lens axis is r and the focal length of the objective lens is f then the angle of incidence is given by sin-1 (r/f). For accurate measurement it will be necessary to employ an objective with a large numerical aperture,

From this point the system can be thought of as a conventional microscope imaging to a detector array. The dashed lines indicate one ray path from a point of the sample surface 216. Varying the input polarisation to the sample will alter the image obtained at a CCD camera 218. By taking a combination of at least three different polarisation states the system can be used to recover a map of the properties of the material.

This system will allow one to obtain ellipsometric material information with good spatial resolution without recourse to scanning the sample. This will give a very rapid mapping of a material surface such as a semiconductor wafer. The system could be envisaged as giving a very rapid spatially resolved map of the variation of, say, oxide thickness on a semiconductor wafer. This could monitor variation and at the same time give statistics such as mean thickness, standard deviation of thickness. The mean thickness value will have a particularly small uncertainty, since averages over a large number of pixels will be used. The system also offers the possibility of scanning over large areas since a good field of view will be acquired with a single measurement.

Fig. 11 shows apparatus 10 for obtaining pure topography information about a sample 12. A laser 14 produces linearly polarised light 16 which illuminates the sample

12 through a beam splitter 18 and objective lens 20.

The reflected light leaves the beam splitter at 22, passes through a lens 24 and is then split by a second beam splitter 26 to pass to the profiler (indicated generally at 28) and to the ellipsometer (indicated generally at 30). As will be described, the profiler 28 produces data which includes pure topography information and material-dependent information. This information is sent (illustrated schematically at 32) to a processor 34, which also receives (indicated schematically at 36) the material-dependent information from the ellipsometer and can therefore produce pure topography information at an output 38.

The profiler section is used to obtain differential phase information. The reflected light from the sample 12 is projected by the lens 24 to a plane conjugate with the sample plane at which the objective 20 is focused. An optical mask 40 is located at this conjugate plane. The light distribution at this conjugate plane contains a magnified version of the distribution across the focal spot at the sample. If the phase of this distribution is compared at different positions placed symmetrically either side of the optical axis the phase difference between the two positions will give a representation of the differential phase on the sample surface. This may be understood by imagining the focal spot on the sample crossing a phase step (such as the edge of a metal overlay). One half of the image of the reflected spot will reflect the phase value on one side of the spot while the other side of the image of the focal spot will reflect the phase on the other side of the phase step. Clearly then a phase difference will be apparent which is representative of the sample structure. On the other hand, if the sample is uniform (flat) then the phase of each point in the conjugate plane will be the same and no phase difference will arise. In order to measure the differential phase it is necessary to measure the phase at the two complementary positions. This may be performed using an interferometer configuration.

The mask 40 is used to select light at two positions in the conjugate plane. These positions are located symmetrically to either side of the optical axis. The selected light then passes through a transforming lens 41 to project a Fourier transform of the light distribution emerging from the mask 40 on to a charge coupled device (CCD) camera 42. Two points in the mask will produce a set of optical interference fringes on the CCD camera whose modulation depth and phase is indicative of the amplitude ratio and phase difference of the

light, emerging from the two apertures. The periodicity and direction of the fringe pattern is determined by the separation and orientation of the two interfering apertures. A simple digital Fourier transform operation allows the amplitude ratio and phase difference to be readily calculated.

Using the profiler 28, the mask will be placed in the plane conjugate to the focal plane. We now consider that we can measure the amplitude and phase response as a function of scan position for a detector placed at two different positions in the conjugate image plane. In practice this can be achieved using a mask with two apertures spaced to either side of the optical axis, and an optional third reference aperture on the axis. The amplitude and phase of the fringes formed is then measured/compared to the reference placed axially, if available. A suitable mask arrangement is depicted in Figure 12. Assuming we have two independent outputs corresponding to slightly different transfer functions arising from the different aperture positions, we may write the two outputs as complex numbers thus:

$$i_1(x_s) = a_1(x_s)\exp(j\phi_1(x_s))$$

$$i_2(x_s) = a_2(x_s)\exp(j\phi_2(x_s))$$

These two outputs may be represented as the Fourier transform of the object function T(m) and the two transfer functions $C_1(m)$ and $C_2(m)$, which correspond to the response using the two displaced detectors 37, 39. The responses $i_1(x_s)$ and $i_2(x_s)$ can therefore be represented as:

$$i_1(x_s) = F^{-1}\{C_1(m)T(m)\}$$

$$I_2(x_s) = F^{-1}\{C_2(m)T(m)\}$$

Clearly in the absence of microphonics the response from each detector allows the function T(m) to be recovered with a simple Fourier transform. The problem is that the microphonics destroy this information, so it is necessary therefore to develop a method to recover the function T(m) while retaining common path information. If the two responses are divided the microphonics which are common to each arm cancel. After division of the two outputs the resulting expression may be written as:

$$i_0(x_s) = \frac{i_0(x_s)}{i_2(x_s)} = \frac{a_1(x_s)}{a_2(x_s)}\exp(j(\phi_1(x_s) - \phi_2(x_s)))$$

Using the Fourier representation for $i_1(x_s)$ and $i_2(x_s)$ allows one to calculate T(m) in terms of an integral equation.

$$F\{i_0(x_s)\}*C_2(m)Tm(m) = C_1(m)T(m)$$

This equation may then be made discrete and solved by a standard procedure such as singular value decomposition. Once T(m) has been recovered the response that would have been obtained if another transfer function had been used can simply be obtained by performing the appropriate Fourier transform with the desired transfer function.

In order to perform this inversion it is necessary to have two independent inputs. This can be achieved with the interferometer described here.

If two independent values are not available and only the phase difference is known then the division cannot be carried out exactly. However, for weak phase objects the amplitudes in each arm are similar so that the phase difference gives a good approximation to the quotient and the procedure described above will work when the differential phase only is known.

Finally, it should be mentioned that the method does not require a differential configuration and any common path configuration with the potential for independent inputs may be used.

Other forms of differential interferometer can be used to extract the phase difference to perform stage (1) of the process.

Measurements of the fringes on the CCD camera are sent to the processor 34 where they may be processed digitally.

Step (2) of the extraction of true topography set out above can be performed using the ellipsometer section 30. This incorporates a transforming lens 50 which, together with the lens 24 and objective 20 form a lens system having a back focal plane at which a second mask 52 is located. The back focal plane of the lens contains information represented by the position of light reaching the mask 52, as indicated schematically in Fig. 13a. Light may arrive at any position around the optic axis 54, for instance at positions 56 and 58. The radial position away from the axis 54 corresponds to the angle of incidence of the light illuminating the sample 12, whereas the azimuth angle corresponds to the polarisation state of the illuminating light. For linearly polarised incident light along the Y axis, s-polarised

light will arrive at a point along the X-axis (such as the position 56) whereas p-polarised light will arrive along the Y-axis (such as the position 58). Light is focused by lens 53 on to a charge-coupled device 55.

The optical field in this plane therefore contains all the information required to extract the ellipsometry parameters Ψ and Δ. One method we propose to achieve this end is to employ a mask arrangement as depicted in Figure 13b so that the amplitude ratio ($\tan\Psi$) and the phase difference, Δ, may be extracted from the amplitude and phase of the fringes projected via the transforming lens 50 into the CCD camera. These values allow the refractive index of the material to be extracted so that the phase shift associated with the material properties may be readily calculated.

Fourier plan ellipsometry allows one to extract the material information whilst retaining the full lateral resolution associated with the numerical aperture of the lens. other methods are available to extract the parameters Ψ and Δ, involving either interferometry or polarising elements. The aperture method described here allows the phase difference Δ to be represented as a shift in the interference fringes, which is not affected by any intensity nonuniformity of the light beam.

Nevertheless it is important for successful extraction of topography to be able to determine the material properties with the full spatial resolution associated with the lens, for which Fourier plane ellipsometry is the best available method, regardless of the detection method used in the back focal plane.

Although specific embodiments of the invention have been particularly described, various modifications may be made within the ambit of the invention. For example, although the use of lenses has been described for focussing radiation on to specimens under test, other means such as holograms may be used for this purpose. Such alternative means may be of particular value when the surface under test departs substantially from a flat plane.

Claims

1. Optical measuring apparatus comprising a source of optical radiation (2) beam producing means (HDE) for deriving from said source of optical radiation a primary beam (4) and a secondary beam (6) **characterised in that** said primary beam (4) is directed on to an object (8) in order to interrogate the local structure of the object and said secondary beam (6) is directed on to said object to serve as an optical reference, optical processing means (HDE) for deriving from said primary and said secondary beams after reflection from said object a tertiary and a quaternary beam and combining means (HDE) to combine said tertiary and said quatenary beams to obtain an optical signal indicative of the structure of said object in the vicinity of the surface thereof.

2. Optical measuring apparatus according to claim 1 **characterised in that** said beam producing means comprises a holographic diffractive component (HDE) adapted to produce a zero order collimated object beam (4), and a +1 order convergent beam (6) to serve as a reference beam, further processing means (HDE) for generating from said object beam and said reference beam upon reflection from said object, respective collimated component beams having a difference in their propagation directions, combining means to combine said two collimated component beams to obtain an interference pattern indicative of the structure of said object in the vicinity of the surface thereof.

3. Optical measuring apparatus according to claim 2 **characterised in that** it includes means to extract the average phase difference of the collimated component light beams by taking the Fourier transform of a captured intensity pattern.

4. Optical measuring apparatus according to claim 2 **characterised in that** it includes a photodiode array to capture a single fringe of said infringement pattern and an analogue quadrature signal processing apparatus to derive a phase value therefrom.

5. Optical measuring apparatus comprising a source of optical radiation (2) beam producing means for deriving from said source of optical radiation a primary beam (4) and a secondary beam (6) **characterised in that** it includes ellipsometer apparatus comprising lens means (20) operable to focus light reflected from a sample to a back focal plane, selection means (40) operable to select light of at least two different polarities from light arriving at the back focal plane, and measuring means (42) for measuring parameters of the selected light to provide information from which properties of the sample may be

calculated.

6. Optical measuring apparatus according to claim 5 **characterised in that** the measuring means further comprise means operable to cause the selected light to interfere.

7. Optical measuring apparatus according to claim 6 **characterised in that** the measuring means is operable to measure the amplitude and phase of fringes caused by the interference.

8. Optical measuring apparatus according to claim 5 **characterised in that** the selection means comprises a mask located at the back focal plane and open at positions corresponding to selected polarities, whereby light of other polarities is blocked by the mask.

9. Optical measuring apparatus according to claim 5 **characterised in that** the selection means comprises a mask, an opening in the mask through which selected light may pass, and separation means operable to separate p-polarised and s-polarised components of light passing through the mask opening.

10. Optical measuring apparatus according to claim 9 **characterised in that** the separation means serves to separate the components spatially .

11. Optical measuring apparatus according to claim 10 **characterised in that** the separation means comprises a Wollaston prism.

12. Optical measuring apparatus according to claim 5 **characterised in that** the selection means comprises phase separator means operable to apply a differential phase shift to the selected light.

13. Optical measuring apparatus according to claim 12 **characterised in that** the phase separation means comprises a Pockel cell.

14. Optical measuring apparatus according to claim 13 **characterised in that** the Pockel cell is selectively operatable to vary the differential phase shift to allow respective sets of measurements to be taken by the measuring means.

15. Optical measuring apparatus according to claim 5 **characterised in that** it includes lens means to bring the separated components together to produce interference.

16. Optical measuring apparatus according to claim 15 **characterised in that** the lens means comprises polariser means aligned with its pass axis bisecting the angle between the p-direction and s-direction.

17. Optical measuring apparatus comprising a source of optical radiation (2) beam

producing means for deriving from said source of optical radiation a primary beam (4) and a secondary beam (6) **characterised in that** it includes profile measuring apparatus comprising lens means operable to focus light reflected from a sample to a conjugate plane, selection means operable to select light at two different positions in the conjugate plane, and measurement means for measuring parameters of the selected light from which profile information relating to the sample may be obtained.

18. Optical measuring apparatus according to claim 17 **characterised in that** the selection means may comprise a mask having openings at two positions.

19. Optical measuring apparatus according to claim 18 **characterised in that** the two positions are symmetrically located either side of the optical axis of the system.

20. Optical measuring apparatus according to claim 19 **characterised in that** the measuring means comprises means operable to cause the selected light to interfere.

21. Optical measuring apparatus according to claim 20 **characterised in that** the measuring means further comprises transforming lens means operable to project a Fourier transform of the light passing through the lens to a plane at which optical interference fringes are formed.

22. Optical measuring apparatus comprising a source of optical radiation having means (207) to direct said radiation on to a sample **characterised in that** said apparatus includes selection means (200, 204, 208, 212) to select the polarity and direction of incidence of said beam on to said sample and detection means (218) to detect radiation from said beam scattered by selected regions of the surface of said sample.

23. Optical measuring apparatus according to claim 20 **characterised in that** means for producing said primary and secondary beams comprises a plano-convex lens (190) having a central planar region on its curved surface.

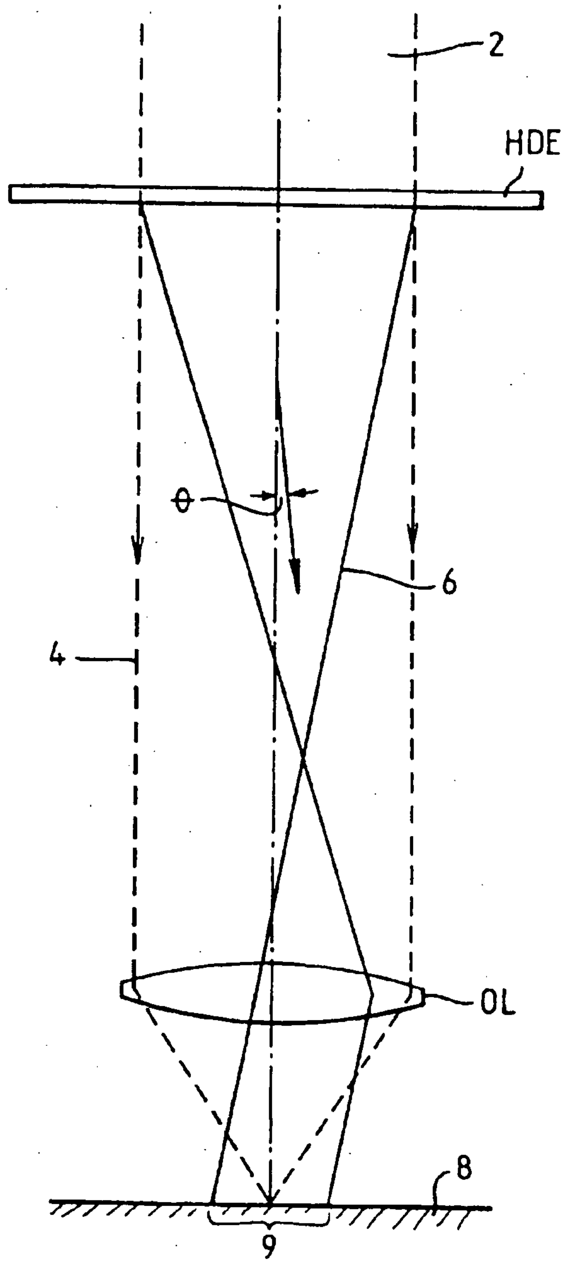

Fig.1

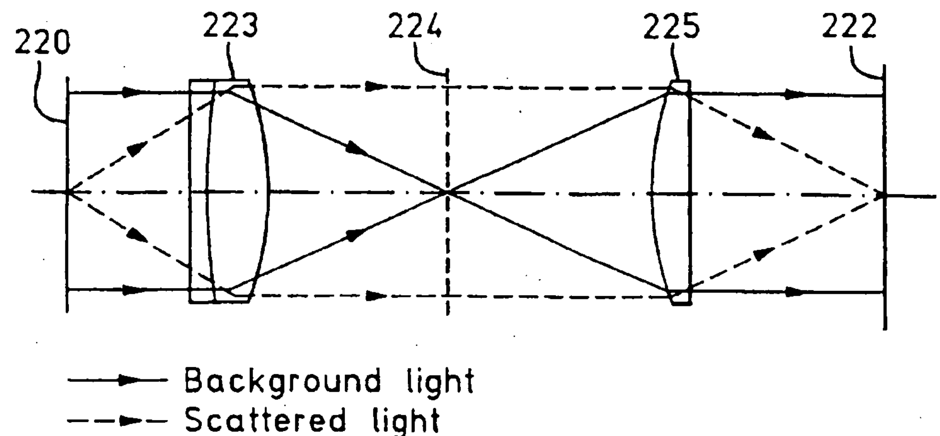

Fig. 2

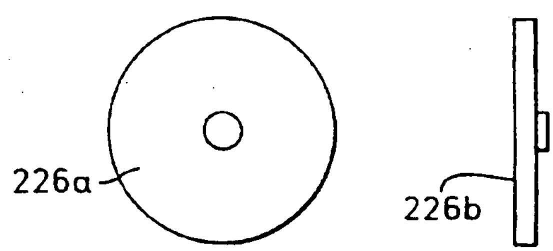

Fig.3a Fig. 3b

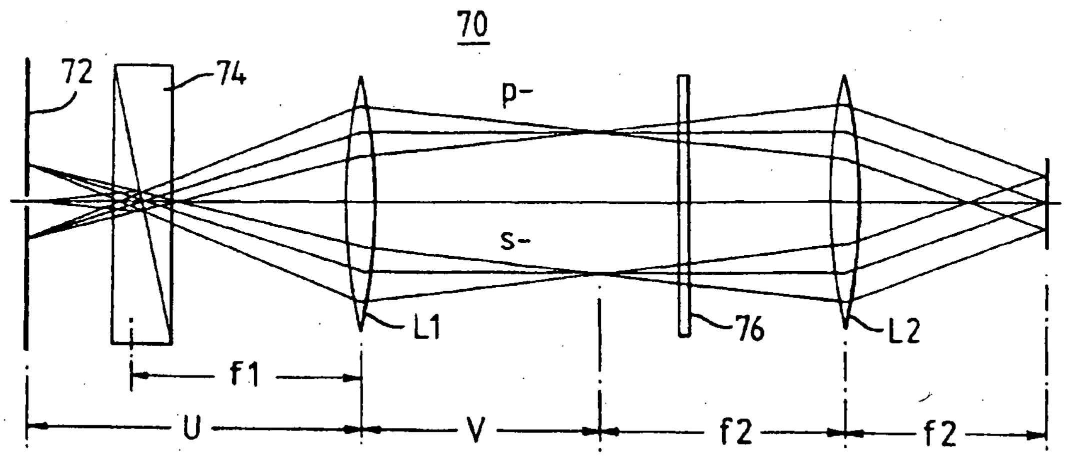

Fig 4

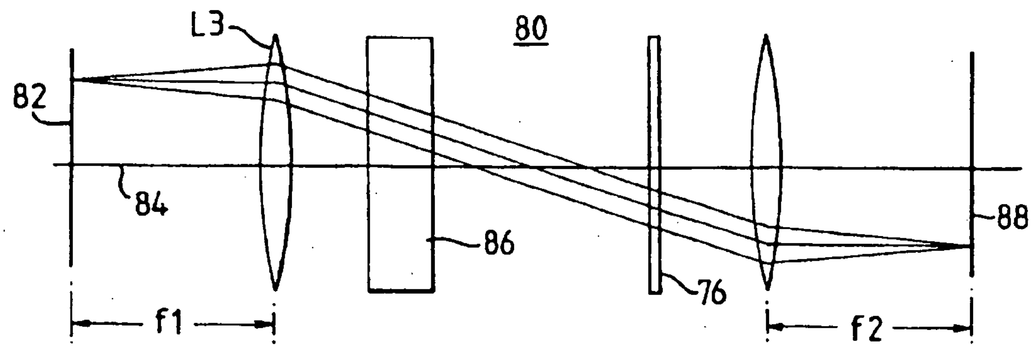

Fig 5

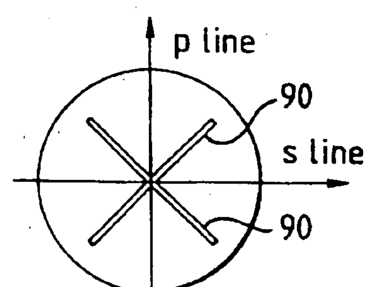

Fig 6

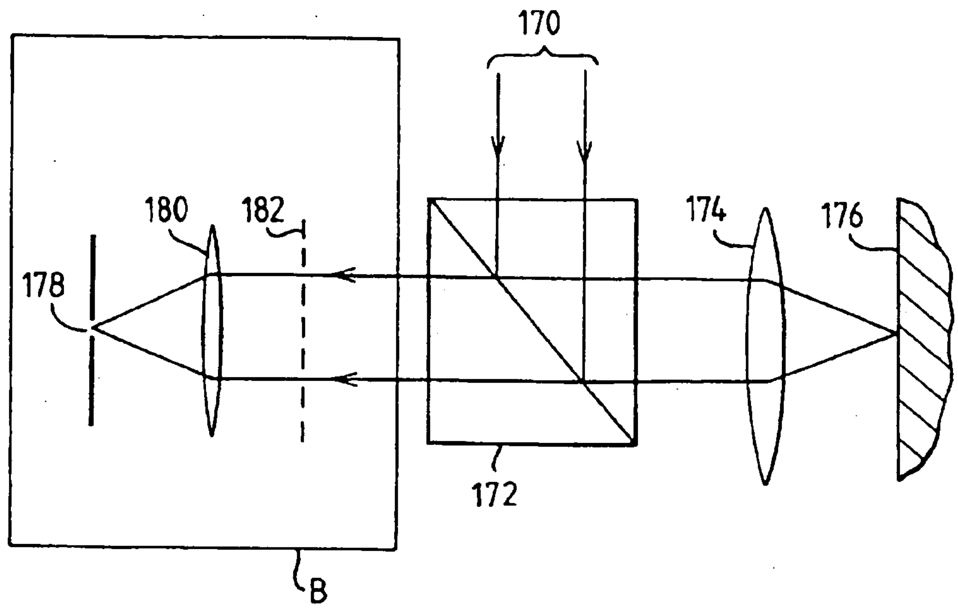

Fig. 7

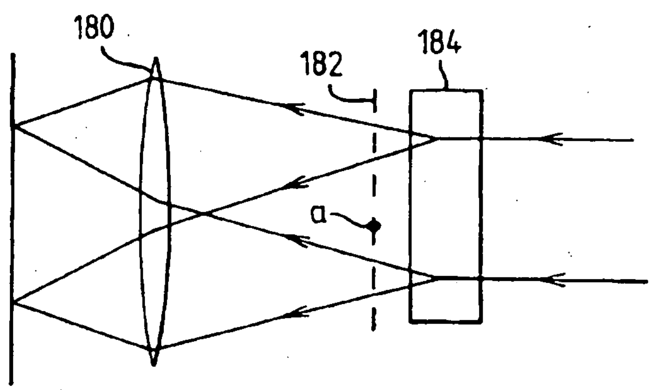

Fig. 8

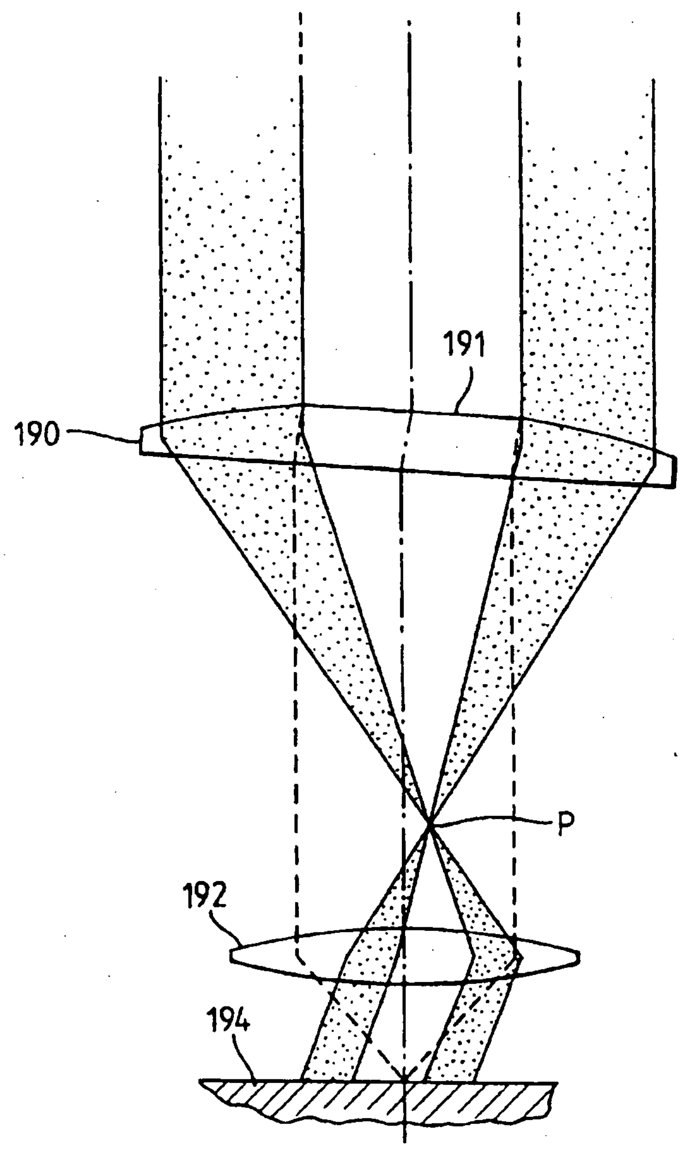

Fig. 9

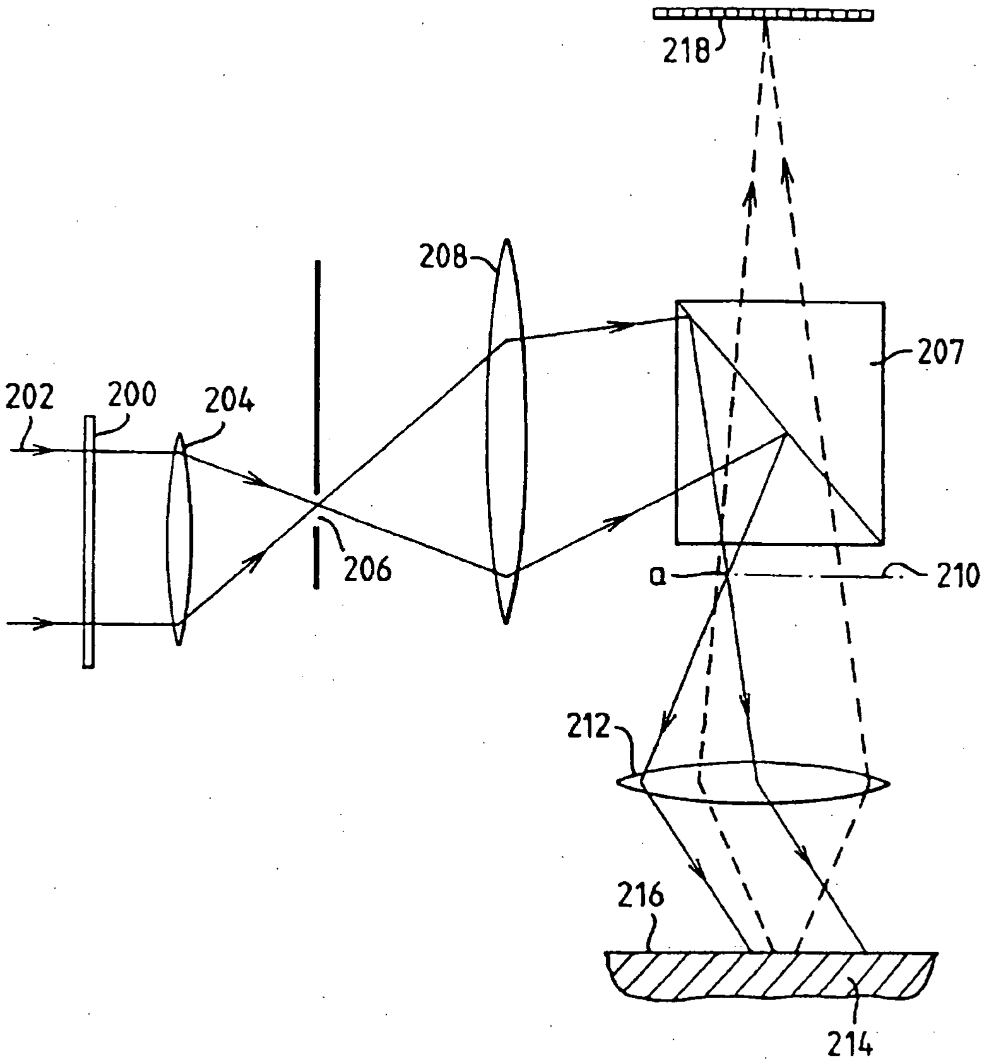

Fig. 10

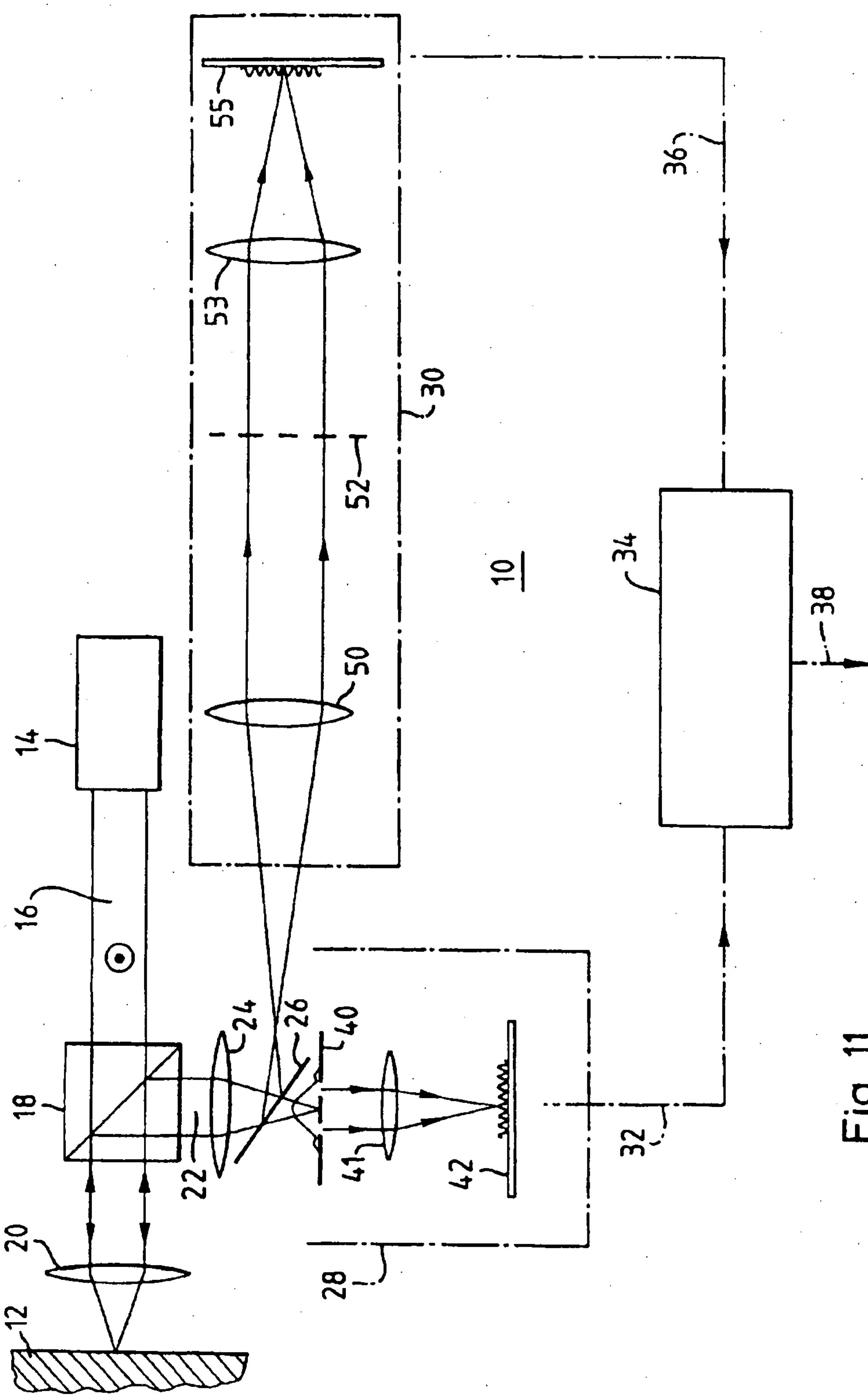

Fig. 11

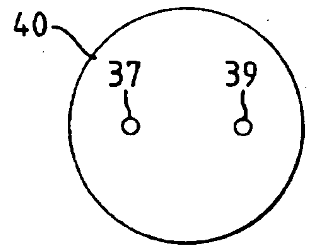

Fig. 12

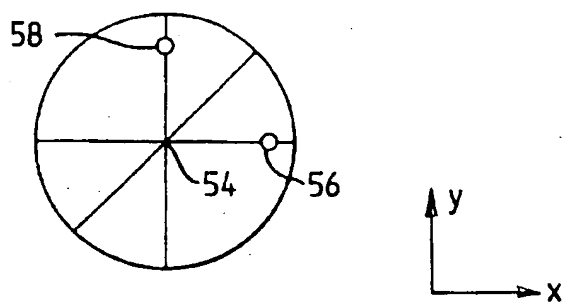

Fig. 13a

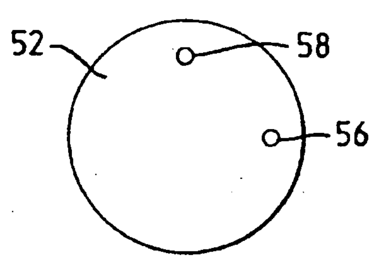

Fig. 13b

INTERNATIONAL SEARCH REPORT

International Application No
PCT/GB 97/01353

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 G01B11/24 G01B11/30 G01N21/21

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 G01B G01N G01J

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	OPTICAL ENGINEERING, vol. 33, no. 4, April 1994, BELLINHAM, WA, US, pages 1078-1083, XP000440045 M. YAMAGUCHI, K. MATSUDA: "Interferometric straightness measurement system using a holographic grating" ---	1
A	US 4 905 311 A (M. HINO, Y. BESSHO, M. KONDO) 27 February 1990 see the whole document; ---	5,17
A	PATENT ABSTRACTS OF JAPAN vol. 10, no. 371 (P-526) [2428] , 11 December 1986 & JP 61 164105 A (HITACHI LTD.), 24 July 1986, see abstract ---	5,17

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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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"&" document member of the same patent family

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Date of the actual completion of the international search	Date of mailing of the international search report
25 August 1997	03.09.97

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+ 31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+ 31-70) 340-3016	Visser, F

International Application No
PCT/GB 97/01353

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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Information on patent family members

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PCT/GB 97/01353

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